Ferdinand Braun and the Cathode Ray Tube

The "indicator tube" developed by Braun in the 1890's measured electrical quantities by the deflection of an electron beam. It was an ancestor of the oscilloscope and television picture tube

by George Shiers

Two signal events in the history of physics were the outcome of experiments with cathode ray tubes: the discovery of X rays in 1895 by Wilhelm Konrad Röntgen and the discovery of the electron in 1897 by J. J. Thomson. In the same period a German experimenter, Karl Ferdinand Braun, contrived a refined cathode ray tube capable of measuring certain electrical quantities. Braun called his invention a cathode ray indicator tube; in it the cathode rays were confined to a narrow beam and directed in such a way that they produced a luminous pattern on a fluorescent screen at one end of the tube.

Braun intended his device for the visual study of alternating electric currents of relatively low frequency. It has since become an instrument of outstanding usefulness in many fields of science and engineering. The lineal descendant of the indicator tube is the laboratory oscilloscope, but many other devices now commonplace in electronics technology also derive from Braun's invention. Among them are the radar display screen and the television picture tube.

The effects of an electrical discharge in a rarefied gas were well known in the 1890's. Preceding Braun's experiments were almost 200 years of enchantment and mystification with the changing patterns of color and light observed in exhausted globes and tubes.

In 1705 Francis Hauksbee produced a "fine purple light" inside an exhausted globe of glass by rotating and rubbing the globe. From Hauksbee's whirling sphere were derived the powerful friction machines that became the standard generators of electricity throughout the 18th century. Experiments with these machines in the 1740's created interest in many electrical phenomena, including demonstrations of luminous displays inside partially evacuated flasks and globes.

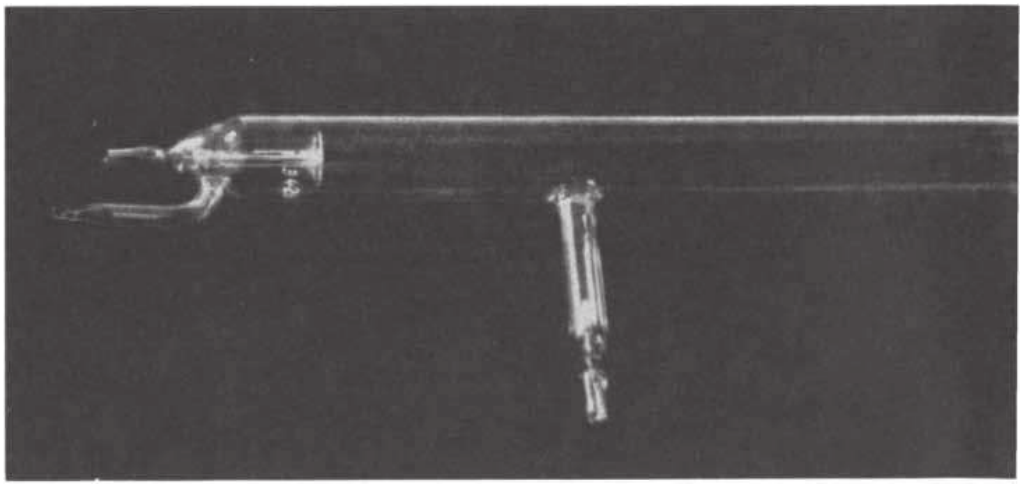
In an attempt to discover how well a vacuum conducts electricity William Watson in 1751 constructed an evacuated glass tube containing two metal plates, or electrodes. He reported that the discharge observed during his experiments was "a most delightful spectacle... of a bright silver hue." In another experiment with a curved glass tube he observed an "arch of lambent flame."

In succeeding years it was demonstrated that the color of the glow depends on the kind of gas in the tube and on its pressure. It was found that with a suitable degree of vacuum the continuous body of luminescence breaks into striations, the bright regions separated by darker ones. A bright light around the negative electrode, or cathode, was also noted [*see illustration on page 94*].

Experiments at the lowest pressure then obtainable indicated that a vacuum is a nonconductor. When air was admitted to the tube, the invisible discharge became a "beautiful green," which, as more air entered, changed to blue and then to indigo and violet. These were important observations, but the more substantial discoveries that led to applications and to a theoretical understanding of these phenomena could not be made until better vacuum pumps and improved glass tubes became available a century later.

In 1855 Heinrich Geissler, a German instrument maker and glassblower, invented a pump in which a column of mercury acted as a piston, producing a better vacuum than had previously been possible. Two years later he fabricated closed glass tubes of high vacuum with wires leading from enclosed electrodes sealed permanently in the glass envelope.

Geissler worked with Julius Plücker, a physicist and mathematician, at the University of Bonn. Plücker quickly applied the new sealed tubes to the investigation of electrical discharges in gases at low pressure and made the important discovery that a magnet influences the glow. When a magnet was placed near



BRAUN INDICATOR TUBE, made in 1897, is a slightly modified version of the instrument employed by the inventor in his initial experiments. The cathode is at the extreme left; the anode is in the small tube protruding from the neck. The viewing screen, a sheet of trans-

the negative electrode, the light spread out in a pattern similar to that assumed by iron filings in a magnetic field. To a large extent it was the joint work of Geissler and Plücker that led, before the end of the century, to the discovery of X rays and the discovery of the electron and to Braun's beam-deflection instrument.

Related experiments were made at the same time in England by John Peter Gassiot, often in collaboration with Michael Faraday, in some cases with tubes made by Geissler. Taken together, these investigations showed that the cathode was the source of certain emanations, although their character was not yet understood. These "negative rays" behaved like a flexible conductor in the way they reacted to a magnetic field; they caused a rarefied gas to glow, and they produced a blue or green light where they struck the glass of the enclosing tube.

Plücker's research was continued by his colleague Johann Wilhelm Hittorf, who described other characteristics of the discharge in 1869. With the better vacuum then available he observed further changes in the discharge as lower pressures were achieved, as well as characteristics of the glow in the vicinity of the cathode. Hittorf also discovered that an object placed in front of the cathode cast a shadow in the fluorescent glow on the opposite wall of the tube. This was a fundamental observation, since it indicated that the "glow rays," as Hittorf called them, were propagated in straight lines from the cathode.

In the 1870's Eugen Goldstein began a series of investigations with discharge tubes that he continued for many years. He showed that the impact of cathode rays on coated plates mounted inside the tube produced chemical changes. He studied cathode materials; more important, he demonstrated that the rays were emitted perpendicularly to the surface of the cathode and that they could be made to converge (that is, they could be focused) by employing a concave cathode. In 1876 Goldstein introduced the term *Kathodenstrahlen,* or cathode rays.

Interest in electrical discharges in vacuum tubes reached a peak in 1879, when William Crookes gave a series of novel demonstrations. Using more than a dozen kinds of tubes, including a "shadow tube" that became famous, he illustrated all the features of the discharge previously known, and some new ones, such as the ability of the rays to do mechanical work and to produce heating.

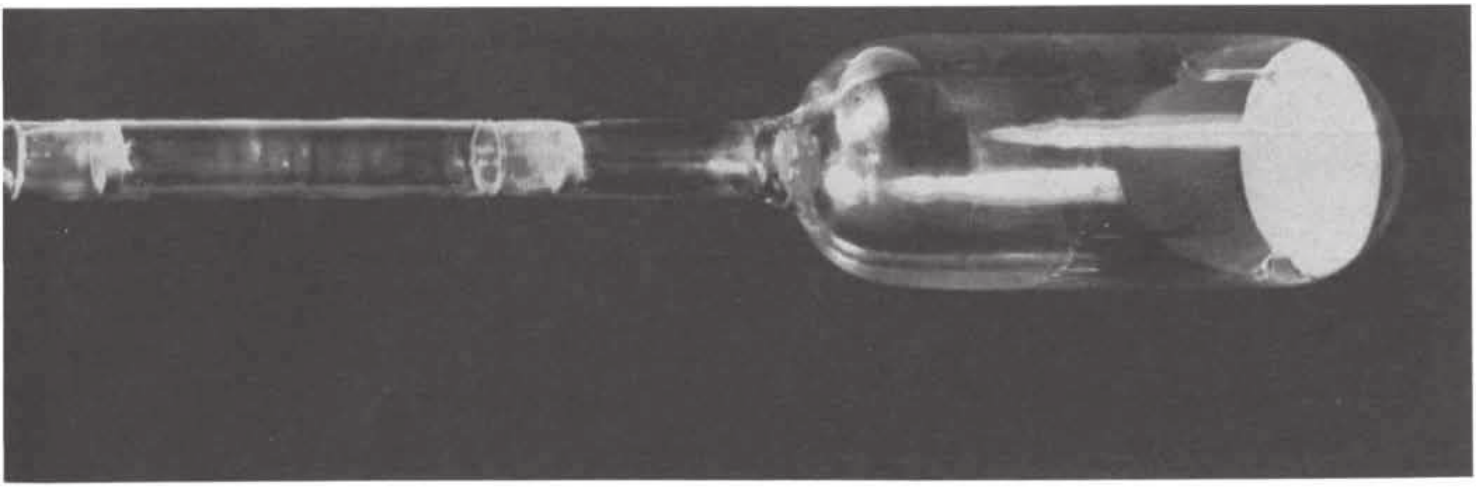
In some of his tubes Crookes reduced the pressure to a millionth of an atmosphere, so that the discharge was no longer visible. He showed that matter in this rarefied state behaves in a special way. The emission from the cathode was, he believed, a "torrent of molecules"; he called it "molecular light." He announced a theory of a fourth, ultragaseous state of matter, which he termed "radiant matter." Crookes's belief that the radiant matter consisted of negatively charged particles streaming from the cathode exacerbated a conflict between the proponents of two opposing views: those who believed the emissions were particles and those who thought they were waves.

During the 1880's the range of investigations into gas discharges was extended by a series of ingenious experiments. One surprising discovery, made by Heinrich Hertz, was that cathode rays could penetrate thin materials, such as gold leaf. In 1894 Philipp E. A. Lenard confirmed the result of Hertz's experiment by constructing a tube with a window of thin aluminum foil at the end opposite the cathode. He found that the rays passed through this window, and he was able to detect them several centimeters away in air. The following year Jean B. Perrin, experimenting with a tube containing open-ended concentric cylinders, proved that the rays carried negative charges of discrete magnitude. The study of electrical phenomena in discharge tubes had become a frontier of physical science.

By the early 1890's many kinds of vacuum tubes were to be found in laboratories and lecture rooms. Called Geissler tubes, Plücker tubes, Hittorf tubes or Crookes tubes, they were used mainly to demonstrate the novel visual effects of the discharge.

The experiments of a few scientists, however, had objectives more serious than the creation of colorful displays. In 1895 Röntgen was working with a Crookes tube enclosed in black cardboard. He noticed that a nearby screen of fluorescent crystals glowed when the tube was energized. In the next few weeks he studied the invisible radiations from the face of the tube and found that they passed through some opaque substances and could expose photographic emulsions. Late in December Röntgen announced his discovery of the new kind of rays, which he called X rays.

Braun, then director of the Physical Institute at Strassburg (now Strasbourg), turned his attention to X rays soon after he received a copy of Röntgen's paper. Born at Fulda in Germany in June, 1850, Braun had studied at the University of Marburg and had become professor of physics there in 1876. He



lucent mica coated with a luminescent compound, is at right, at the end of the bulbous portion of the glass envelope. Two diaphragms, each with a small aperture in the center, restrict the breadth of the electron beam. (The first indicator tubes had only one diaphragm.) The deflection coil and other devices that were mounted externally are not shown in the photograph. The tube was about 20 inches long.

had spent the next 20 years in various posts at Strassburg, Karlsruhe and Tübingen, and had returned to Strassburg in 1895.

The cathode ray tube was of intense interest during the early months of 1896 as hundreds of workers repeated Röntgen's experiments. Braun was among those enthusiasts, but unlike most of them he was more concerned with the source of the X rays than with the radiation itself. What intrigued him were the emanations from the cathode and their power to excite fluorescence in the glass envelope of the tube.

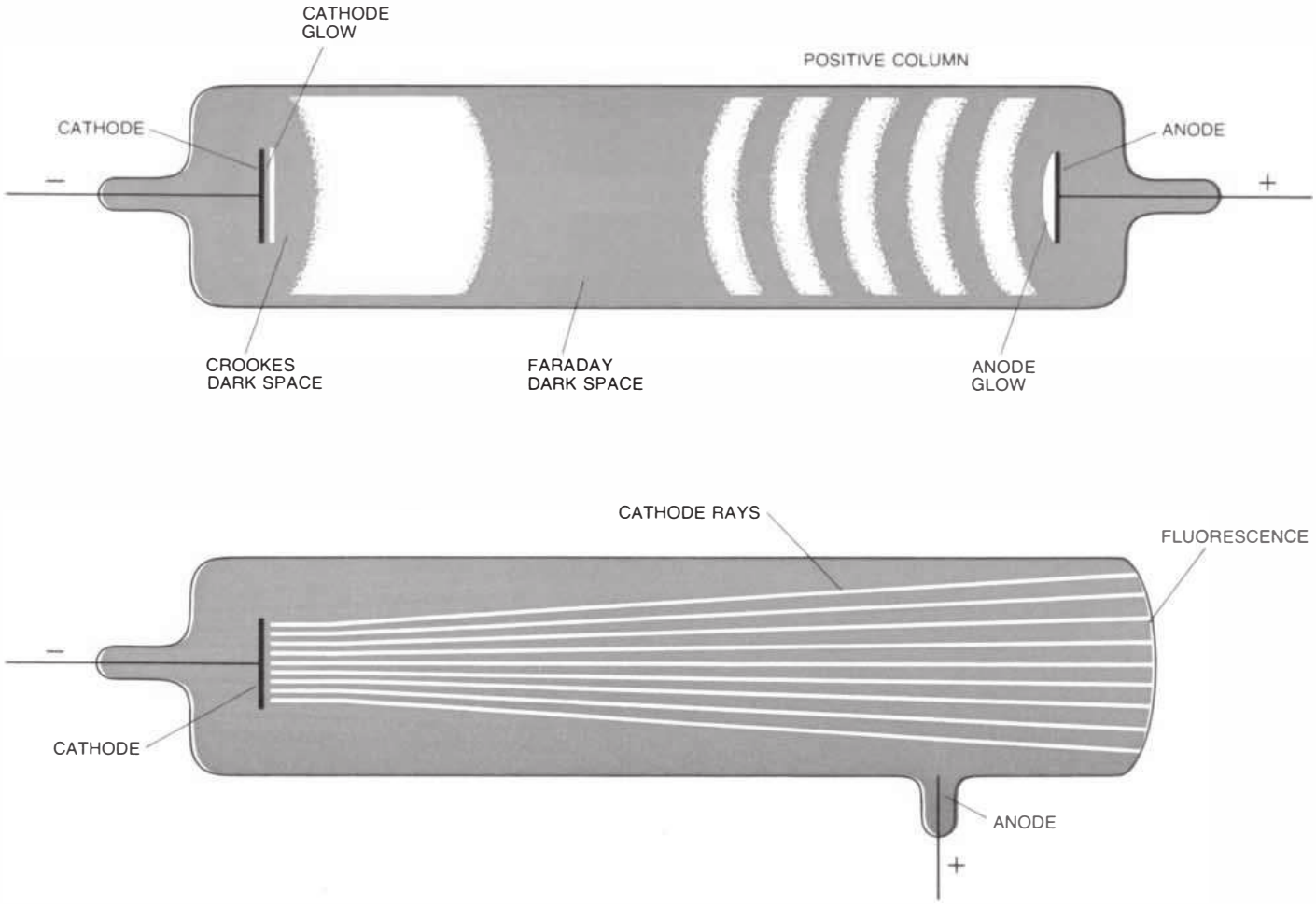
No one had yet controlled these rays in order to make use of the fluorescence, although in 1894 Albert Hess had proposed that they could be of value in magnetic studies. Braun saw in the discharge tube the possibility of a new instrument, a visual indicator of oscillatory and transient phenomena in electrical circuits. The need for such an instrument was already apparent.

By the 1890's central generating stations were providing electric power to many cities and towns. Some newer systems, including the one at Strassburg, supplied alternating current. The periodic nature of this current, which reverses its polarity with every cycle, presented a number of problems of measurement.

The wave form of an alternating current is a curve that shows the instantaneous value of the voltage or current during one cycle. In power systems it is ideally a sine curve, that is, a curve proportional at every point to the sine of the angle through which the alternator shaft has turned. "Phase" is also of interest in power systems; it is the angular displacement between two or more periodically varying quantities, such as voltage and current or two voltages [*see illustration at top left on page 96*]. At that time precise knowledge of these swiftly changing quantities was difficult to obtain.

One laborious method for mapping wave forms consisted in noting a series of voltmeter readings and the corresponding angular positions of the alternator shaft. More refined techniques then being developed employed rotating or vibrating mirrors that displayed the wave form as a curve traced by a beam of light on a screen. In the electromechanical oscillograph, for example, a tiny mirror is attached to the moving coil of a galvanometer, which oscillates in sympathy with the applied voltage. A beam of light reflected from this mirror moves to and fro, and the line of light thereby produced is opened up transversely, or scanned, by a second mirror moving at right angles to the first.

At the frequencies of commercial power systems (usually 50 or 60 cycles per second) the delineation of wave forms was within the capabilities of such early oscillographic instruments. Currents of much higher frequency were of growing interest, however. Special types of alternators furnished electricity of 5,000 or



EFFECTS OF AN ELECTRIC DISCHARGE in an evacuated tube depend on the amount of gas remaining in the tube. At pressures of about a ten-thousandth of an atmosphere (*top*) electrons emitted by the cathode collide with and ionize residual gas molecules, producing a glow in various regions within the tube. With further rarefaction these collisions become infrequent, the bright areas recede toward the anode and the Crookes dark space expands to fill the length of the tube. At about a millionth of an atmosphere (*bottom*) no ionization glow is visible; it is under these conditions that cathode rays are produced. The electrons travel at high velocity, evoking fluorescence in the glass when they strike the end of the tube. The electrons are emitted perpendicularly to the surface of the cathode but diverge slightly as a result of mutual repulsion. Their path is not influenced by the shape or the position of the anode.

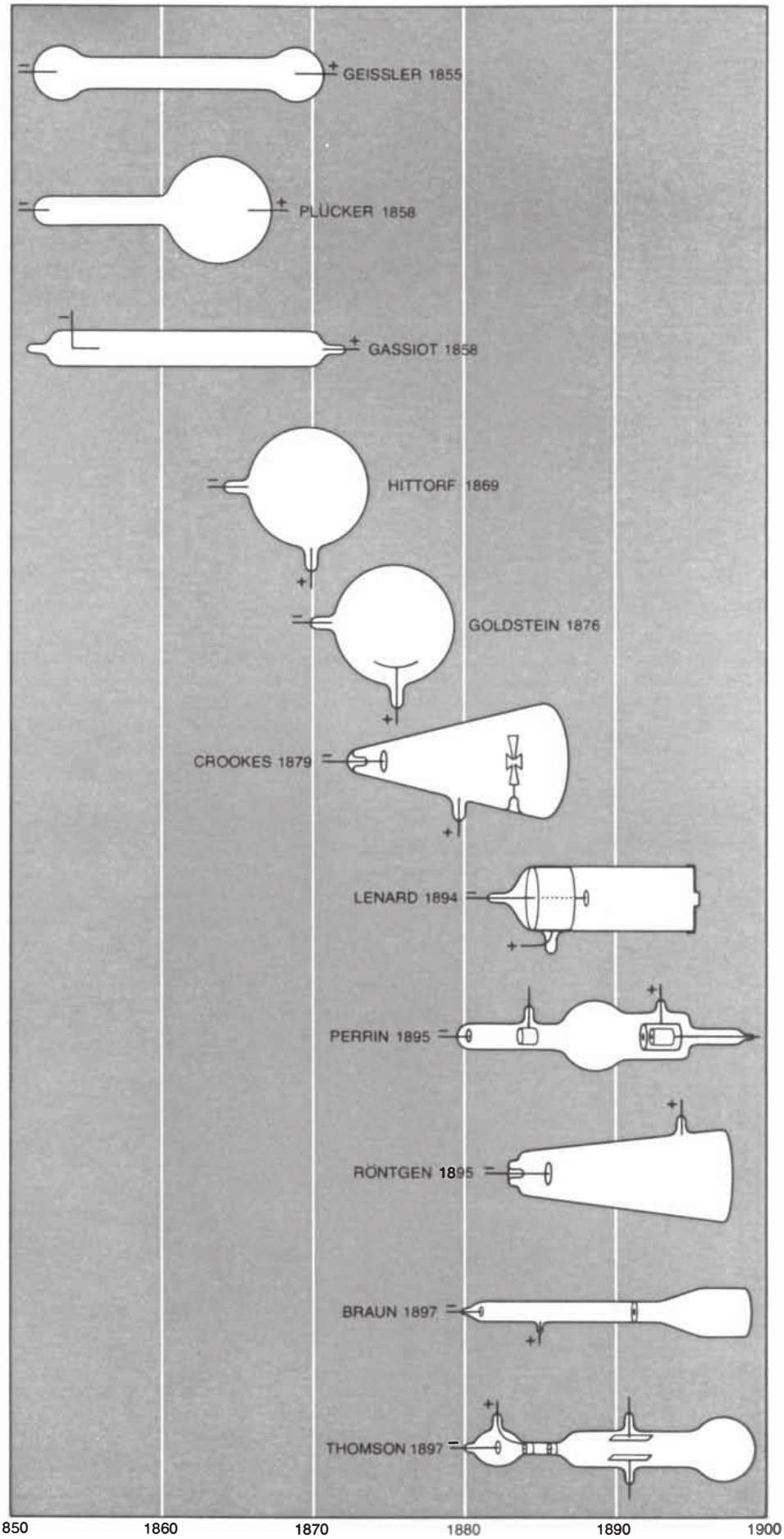
even 10,000 cycles per second. Still higher frequencies were generated by oscillatory circuits incorporating Leyden-jar capacitors and by discharges across spark gaps; these were already in use in the new art of wireless telegraphy. Because of the inertia of their moving parts and because of relatively low resonant frequencies electromechanical instruments could not record oscillations at these high frequencies.

Braun had a long-standing interest in oscillatory phenomena; his doctoral paper, written in 1872, was on the oscillations of strings and elastic rods. The new field of electromagnetic waves, introduced by the work of Hertz in 1888, and the high frequencies obtained from spark-gap generators, both of which attracted other notable investigators, were closely allied with Braun's favorite subject. It is not surprising that he developed an interest in them, nor is it surprising that the lack of a suitable instrument for the study of these phenomena attracted his attention. Braun had often designed original apparatus for his own investigations and for classroom use.

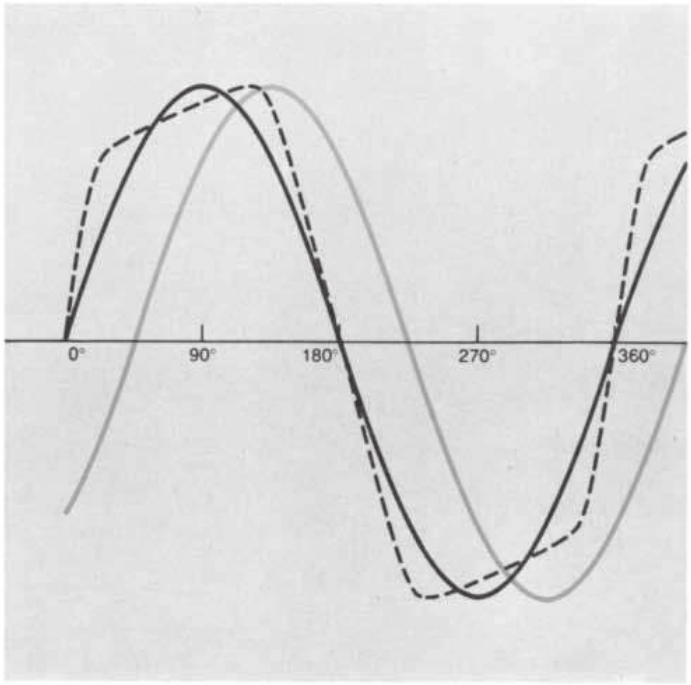
Braun readily perceived that certain features of the cathode ray tube were ideal for adaptation to a wave-form indicator. If the rays were constricted, their impact on a suitable fluorescent screen inside the tube would produce a spot of light instead of a broad luminosity across the entire face of the tube. Because the rays respond to a magnetic field by moving at right angles to the field, the moving spot could be made to oscillate in synchrony with a periodically varying field. The motion of the spot could therefore reflect changes in voltage or current and their relationship to time.

Because such a beam is virtually without inertia, it would respond almost instantaneously to changes in the deflecting force. The beam could also move in any direction across a plane surface and could trace intricate patterns. In these respects it is like light, but in its responsiveness to magnetism it offers an advantage over light.

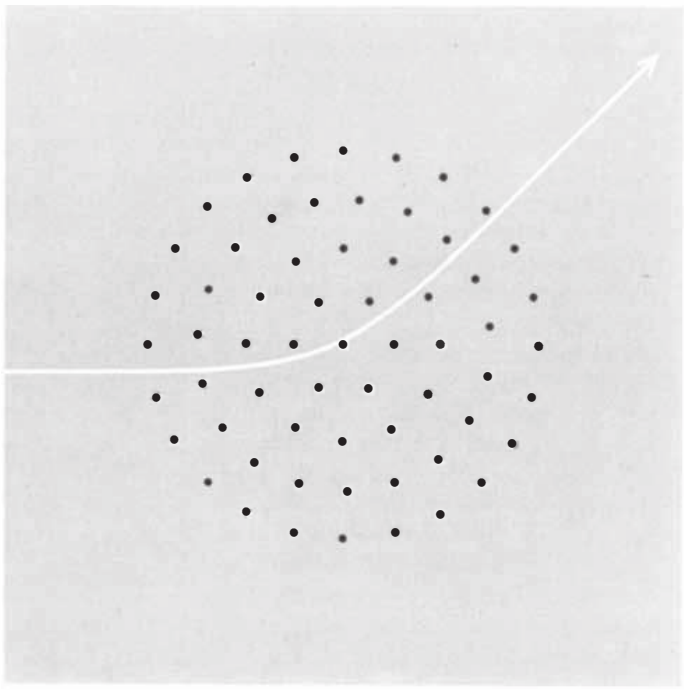
If a device of this kind could be constructed, Braun perceived, it would raise the maximum frequency of graphic indicators by several orders of magnitude. Engineers and scientists would be brought into visual contact with the dynamics of oscillatory circuits. Even in crude form such an instrument would enable one to study short-lived and rapidly changing currents in greater detail and with greater precision than had pre-



STUDY OF ELECTRICITY IN A VACUUM was a productive field of research in the 19th century. Vacuum tubes employed by some of the investigators are illustrated here. This work culminated in the discovery of X rays by Wilhelm Konrad Röntgen, the invention of the indicator tube by Karl Ferdinand Braun and discovery of the electron by J. J. Thomson.



SINUSOIDAL WAVE FORM is generated by an alternator when the instantaneous value of the voltage or current is proportional to the sine of the angle of rotation of the alternator shaft. The Braun indicator tube provided a means of observing such wave forms and of detecting distortion in them (*broken black curve*). It was also capable of measuring the phase relationship of two wave forms; here the solid black curve "leads" the colored curve by 45 degrees.



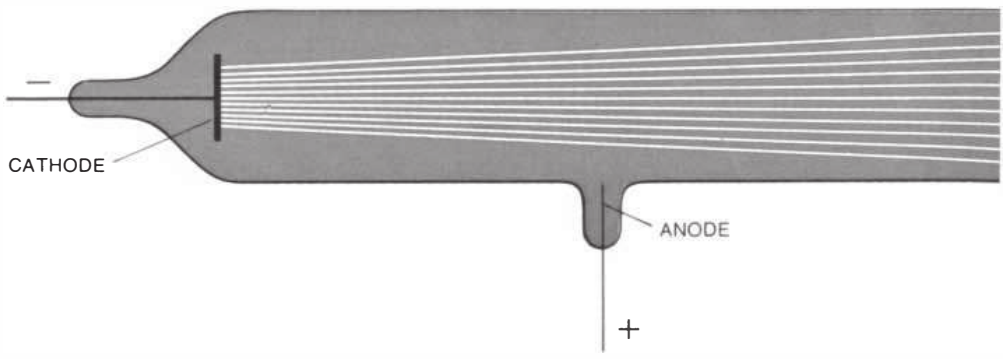
ELECTRON IN A MAGNETIC FIELD follows a path described by a segment of a circle. The field (*black dots*) is perpendicular to the page. While traversing it the electron (*white line*) is deflected onto a circular trajectory whose radius is determined by the strength of the field. The electron enters and leaves the field on straight lines that are tangent to the circle. It is neither attracted nor repelled by the magnet and remains in a single plane parallel to the page.

viously been possible. Such an instrument was, in fact, as essential to electrical science as the telescope, microscope and spectroscope were in other fields.

During the latter half of 1896 Braun designed a tube that would serve his purpose. The basic requirements of the design were already evident: the divergent rays from the cathode would have to be confined to a narrow beam and a fluorescent screen would have to be placed at the end of the tube as a viewing surface. The simplest way to obtain a thin beam was to block most of the rays with a diaphragm or baffle and pass only a small portion through a hole in the center. A tubular segment of the glass envelope would contain the cathode, the restricting diaphragm and an anode at the side; the other half of the tube would be expanded to accommodate the viewing screen. The screen would consist of a thin, translucent disk of mica, coated with a phosphor such as barium platinocyanide or zinc silicate. A coil outside the tube, placed close to the diaphragm and connected to the current being studied, would deflect the beam. Finally, as in other oscillographic methods, a rotating mirror in front of the phosphor screen would be required to translate the line of light produced by the moving spot into a two-dimensional curve.

Braun designed several tubes of varying geometry and had models made in Bonn by Franz Müller, a successor to Geissler. Braun's paper "A Method to Demonstrate and Study the Time Sequence of Variable Currents" was published in *Annalen der Physik und Chemie* in February, 1897. The paper includes a diagram of the tube he favored for experiments [*see illustration below*].

The tube was mounted horizontally in a cradle with the deflection coil near the



FIRST BEAM-DEFLECTION INSTRUMENT was constructed for Braun by Franz Müller in 1897. The deflection coil, mounted athwart the pierced diaphragm, bent the beam upward when energized in one direction and downward when the polarity was reversed. When an

diaphragm and perpendicular to the axis of the tube. The high voltage required to energize the tube was produced by a Töpler influence machine, a descendant of the hand-turned friction generators, or sometimes by an induction coil.

Each experiment required elaborate preparation by Braun and his assistants. When an unsealed tube was used, it had to be laboriously evacuated by a hand-operated mercury pump. Someone had to crank the influence machine or attend to the induction coil. The speed of the rotating scanning mirror had to be adjusted, and sundry connections in the electrical circuits had to be made as each experiment progressed. When all was in order and an alternating current was applied to the deflection coil, a glowing green line about an inch long appeared on the phosphor screen. In the rotating mirror this line was transformed into a faint and flickering curve.

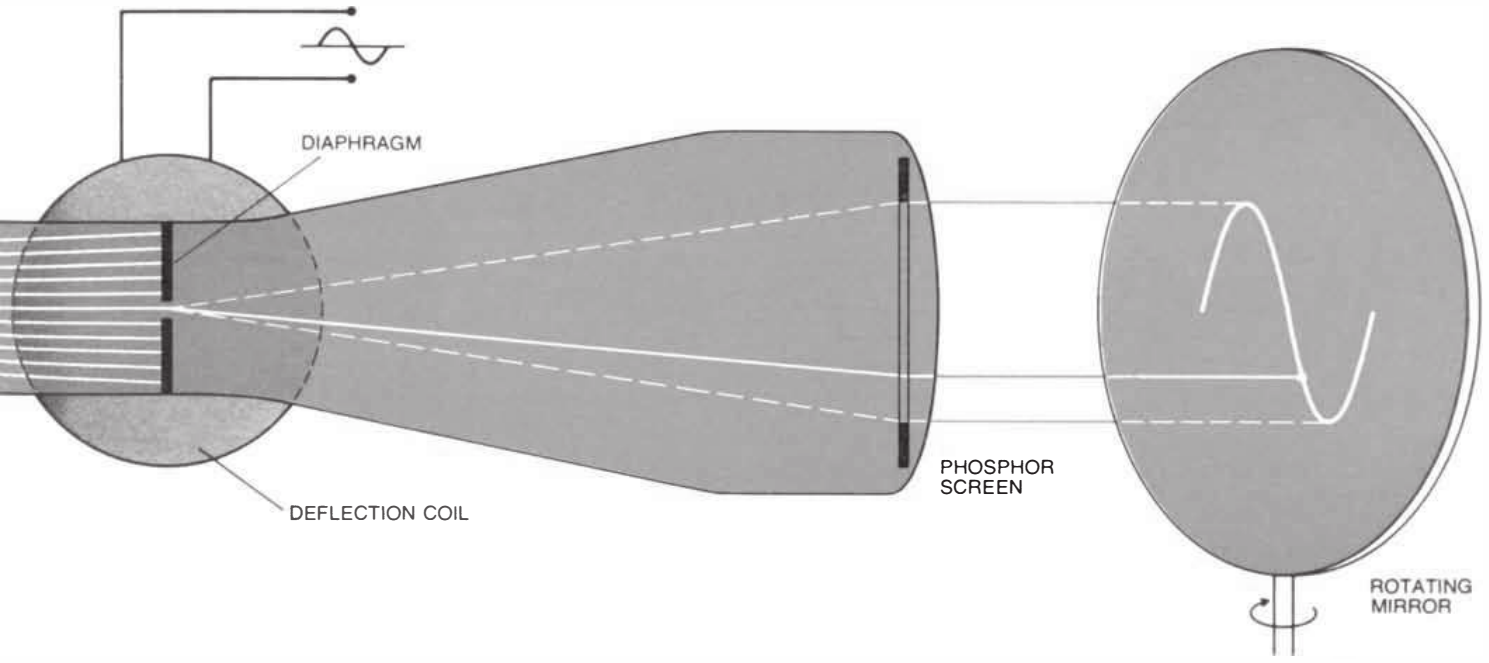
In his initial experiments Braun made use of the Strassburger Centrale power lines (120 volts, 50 cycles per second) to test his instrument. At that time the wave form of some alternators was a kinky curve distorted by the mechanical and magnetic peculiarities of the generating or distribution apparatus. Braun was surprised to discover that the local wave form was virtually sinusoidal. He compared the power-line wave form with the curve produced by a spot of light reflected from a mirror attached to one of the tines of a tuning fork, a standard method of producing a sine wave. In giving diagrams of both curves in his paper he may have been trying to show that his apparatus could perform as well as the better-known arrangement of tuning forks and mirrors.

Having verified the basic performance of the indicator tube, Braun investigated the more complex wave forms of currents in an induction coil. He compared the wave forms in the primary and secondary windings and observed the wave form of the secondary current under various conditions: when the circuit was open, closed or connected to a capacitor. While studying these patterns he noted that the brightness of the spot varied with its velocity across the phosphor screen. A slow trace produced a bright line, whereas a fast movement of the spot resulted in a line so faint that it was not easily seen even in a fully darkened room.

In further experiments Braun showed that the glowing spot could produce Lissajous figures directly on the phosphor screen without an interposed rotating mirror. These closed curves (named for Jules Antoine Lissajous) are created by the simultaneous displacement of the spot by two simple harmonic motions at right angles to each other. Braun obtained a second deflecting force by rotating a magnetized rod in a horizontal plane below the tube. With alternating current from the power lines energizing the deflection coil he observed changing patterns by varying the rate at which the magnet was spun. He readily obtained certain simple patterns, such as a figure eight, which represents a frequency ratio of two to one. He could not demonstrate the higher ratios, however, because at high rotational speeds it became difficult to synchronize the two frequencies.

In a subsequent series of experiments Braun was able to operate the tube as an all-electric instrument, without any moving mechanical parts. Again the scanning mirror was removed, but instead of a rotating magnet a second deflection coil, at right angles to the first, was installed. When the currents in the two coils were in phase (when their peaks and nulls were simultaneous), the resultant forces acting on the beam produced on the viewing screen an oblique line. A small difference in phase produced a narrow ellipse; as the difference increased, the ellipse broadened and, when the two currents were 90 degrees out of phase, became a circle. A phase difference of 180 degrees produced an oblique line perpendicular to the first line. By this method Braun was able to determine the phase displacement between the primary and the secondary winding of an induction coil.

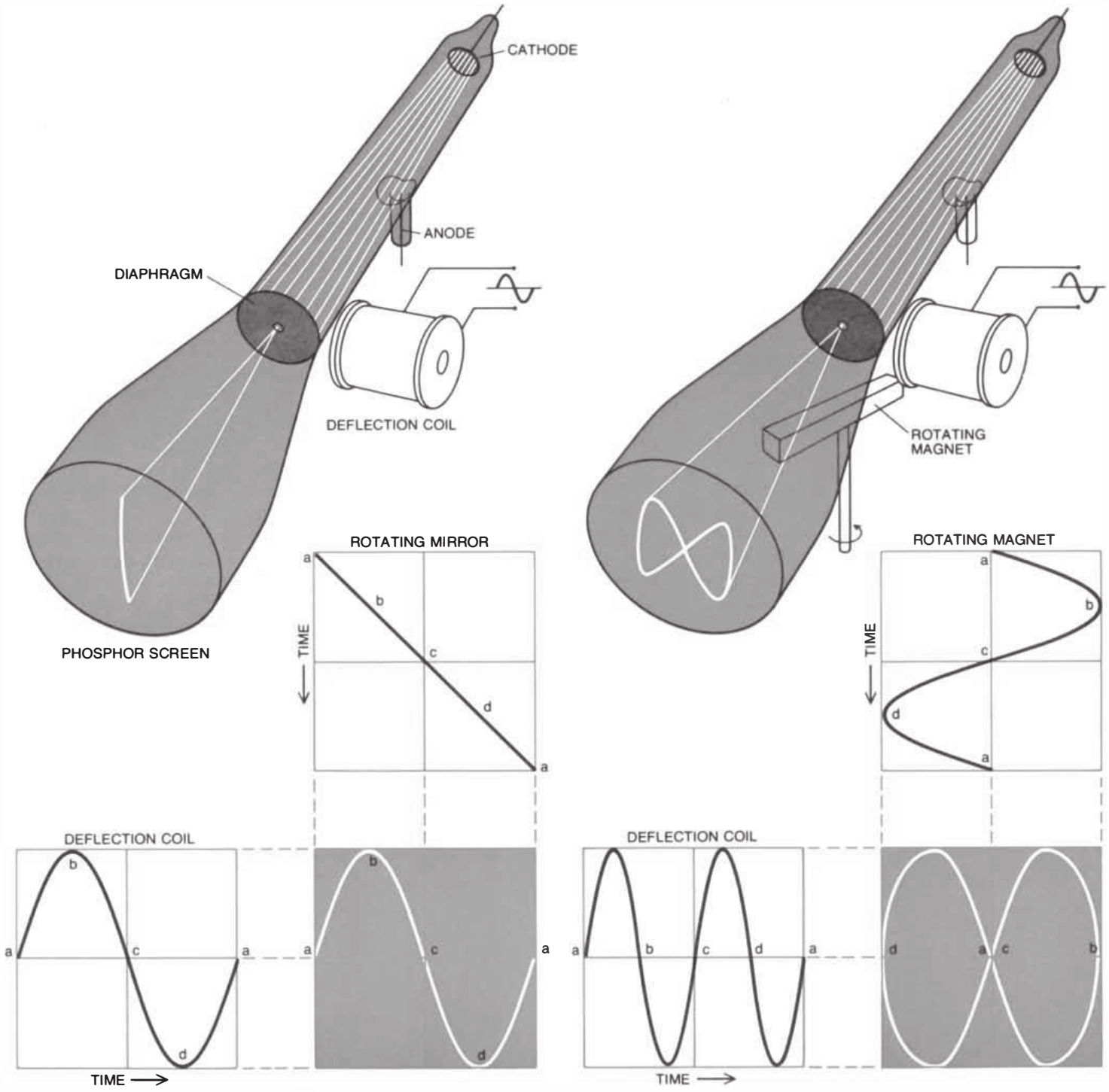
These patterns are modified when the circuit energizing one coil includes more inductance or capacitance than that energizing the other. With one coil in a circuit containing only resistive elements (and the inductance of the deflection coil itself), Braun connected the other coil to an inductor with an air core, to an inductor with an iron core and to a



alternating current was applied to the coil, the resulting motion was too rapid to be detected by the eye and appeared on the phosphor screen as a vertical line about an inch long. In the rotating mirror, however, the line was transformed into an image of the original wave form; the rotation of the mirror added a horizontal component to the motion of the luminous spot, "scanning" it transversely.

capacitance, separately and in combination. The resulting figures graphically confirmed the fundamental theory of reactive electric circuits. When a capacitance was introduced, the patterns were distorted, with peaks and indentations. Braun recognized that these distortions were caused by the superimposition of oscillations of higher frequency generated by the combination of inductance and capacitance in a resonant circuit.

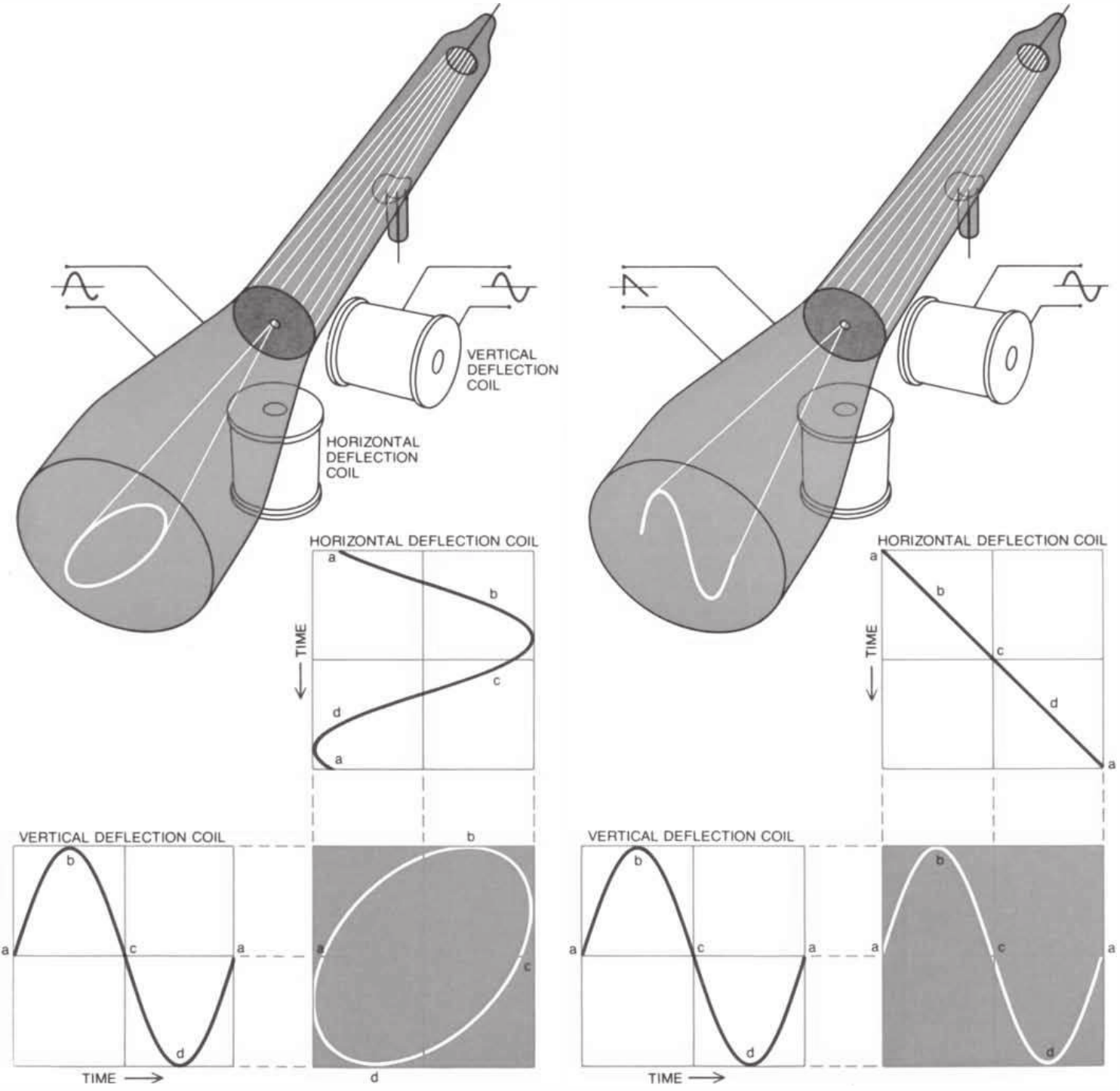
The versatility of the instrument was confirmed in additional experiments on phase displacements with polarized electrolytic cells and on the magnetism induced in long iron bars by direct current and alternating current in movable coils. The response of the tube to a voltage that changes extremely fast was also investigated. When a capacitor is discharged through an inductor, the initial



MODES OF OPERATION of the indicator tube are depicted in the drawings on these two pages. In his first experiments (*left*) Braun deflected the beam only in the vertical plane, relying on a rotating mirror, which is not shown, to scan the image horizontally. The resulting wave form can be analyzed into two components. The vertical component consists of the sinusoidal current applied to the deflection coil; the horizontal component is the motion of the mirror: the image moves across it at a uniform rate, by convention from left to right, returning to its starting position with each half-revolution. In the graph each point on the resulting wave form is determined by the corresponding points on the component curves. For his subsequent experiments Braun eliminated the rotating mirror. By spinning a magnet under the tube while maintaining an alternating current in the vertical deflection coil he was able to obtain Lissajous figures directly on the phosphor screen (*second from left*). These figures are produced whenever two waves interact per-

current is followed by a series of oscillations that is rapidly extinguished. Braun discharged a Leyden jar through the deflection coil and noted that the fluorescent spot moved about half an inch up and then about the same distance down. The rapidity of this motion proved, at least qualitatively (he did not time the discharge), an essential characteristic of cathode rays: their infinitesimal inertia.

In his paper Braun did not discuss the theory of the indicator tube, nor did he explain how he had arrived at its design; the process seems to have been largely intuitive. Following German custom he employed the term "cathode rays" (most English writers called them "negative rays") at a time when the nature of the rays was a matter of speculation and controversy. The issue was soon to be resolved by Thomson, who was then near-



pendicularly to each other; if the ratio of their frequencies is integral, a closed figure is formed. Here the magnet is rotating at one-half the frequency of the deflection coil signal; consequently the figure has two cusps. When a second deflection coil was added to the tube, Braun was able to study phase relationships (*third from left*). The currents are equal in frequency and amplitude but the signal applied to the vertical deflection coil leads the other by 45 degrees; the resulting trace is an ellipse. A further refinement, added by Jonathan Zenneck, one of Braun's assistants, made it possible to display the wave form of one of the deflection signals directly on the phosphor screen, without a rotating mirror (*right*). Zenneck's "time base" scanning system generated a signal that swept the beam of electrons across the screen horizontally at a uniform rate, returning it to the extreme left at the end of every cycle. As the graph of the wave form suggests, the scanning signal is the exact electrical equivalent of the motion of the spinning mirror.

ing the climax of years of work with electricity in gases at the Cavendish Laboratory of the University of Cambridge. Ten weeks after Braun's paper was published Thomson announced his discovery that cathode rays consist of "corpuscles" less massive than atoms and carrying identical negative charges, in other words, electrons.

The success of Braun's pioneering experiments is remarkable in view of the limitations of his apparatus and techniques. Because the cathode was not heated, as it is in most modern tubes, a potential of as much as 50,000 volts was required between cathode and anode to produce cathode rays of sufficient intensity. This large potential caused undesirable leakage currents inside the tube and electrostatic charges on the glass envelope. It also diminished the sensitivity of the tube, that is, the angular displacement of the electron beam for a given deflecting force. As the voltage is increased the velocity of the electrons, and thus their momentum, also increases, so that a larger force must be applied to deflect the beam.

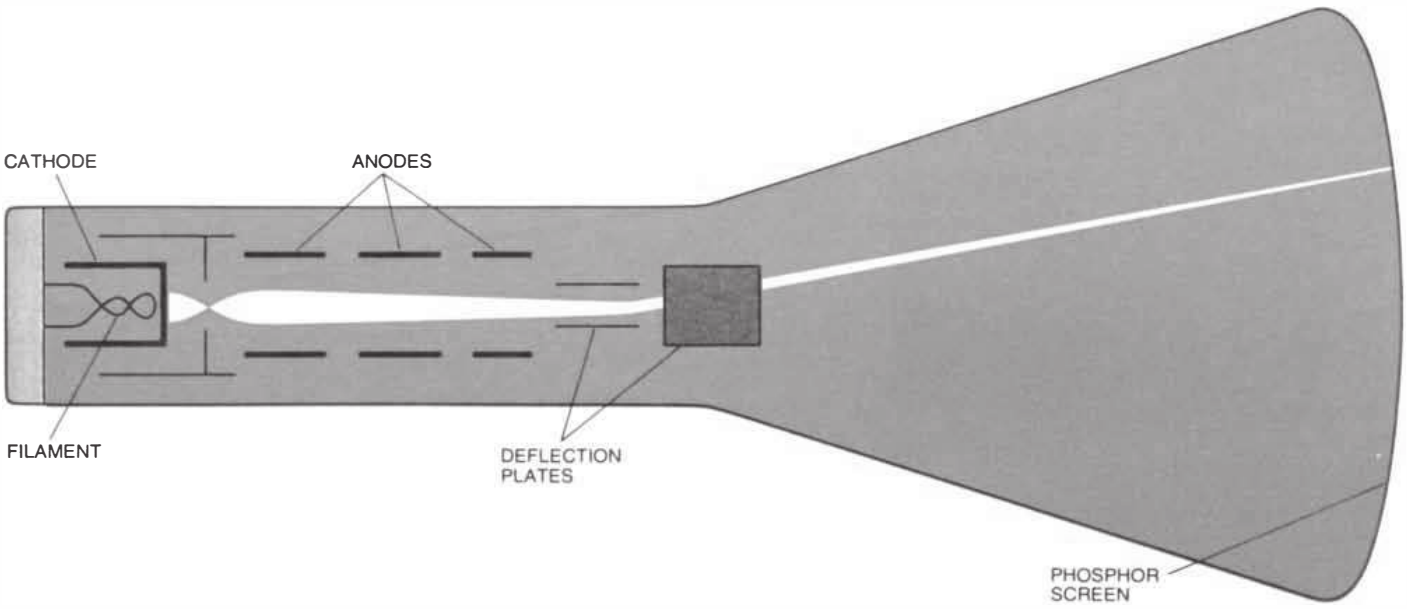
These factors, as well as the inconstant output of the high-voltage source (influence machine or induction coil), caused unstable operation, flickering of the trace and vagueness of the fluorescent patterns. The image was further degraded by the crude method employed to deflect the beam. With a coil on only one side of the tube the magnetic field was asymmetrical; this dispersed the beam so that it produced an elliptical patch rather than a circular spot on the screen. The aperture in the diaphragm governed the size of the spot, but Braun could not control the sharpness of its outline, or definition, since the tube did not provide a means of focusing the beam. Therefore the spot was fuzzy and the trace indistinct, particularly in comparison with the crisp patterns then obtainable by optical methods.

Braun was aware of some of these shortcomings in his instrument. He pointed out that the method required "strong forces," hinted at possible sources of error and suggested certain precautions, such as surrounding the tube with a grounded shield. He nevertheless expressed confidence that the tube offered "definite advantages for many scientific purposes."

Braun's work on the indicator tube was continued by Jonathan Zenneck, one of his assistants. By 1899 Zenneck had designed an improved tube, made photographic records of various traces and invented an electrical method for recursively deflecting the beam on the horizontal axis at a constant rate. This "time base" method of horizontal scanning enabled the instrument to display wave forms without the rotating mirror. Although it did not eliminate all the moving mechanical parts (a motor was still required in the circuit that generated the scanning signal), it enabled the fully constituted trace to be displayed on the phosphor viewing screen inside the tube. During the next few years Zenneck explored the possibilities of the tube in a variety of applications, including the infant art of signaling without wires.

In 1897 public demonstrations in England and Italy by Guglielmo Marconi brought wireless telegraphy to the attention of the world. By the end of that year the new method of communication was being investigated in Germany. Braun's experience with alternating current and his knowledge of oscillatory circuits led him naturally to the new field. He made several contributions of fundamental importance, among them a circuit to couple a spark generator with an antenna system that increased the "energy of action," or radiated power, and greatly extended the range of transmission. He also introduced antennas for directional transmission and reception.

Braun and Marconi were jointly awarded the Nobel prize for physics in 1909 for their contributions to wireless telegraphy. In his acceptance speech Braun described experiments with the cathode ray tube and also spoke of his early investigations of crystalline materials, such as galena and the pyrites. Recalling his own work with these minerals in 1874, and the fact that certain crystals allow current to pass more freely in one direction than in the other, Braun had recognized about 1900 that these substances could rectify high-fre-



MODERN OSCILLOSCOPE TUBE is almost identical in principle with Braun's instrument but is much changed in detail. Electrostatic deflection is substituted for the electromagnetic coils Braun employed, and the single wire anode has been replaced by a series of cylindrical anodes that accelerate the electrons, focus them into a narrow beam and control the brightness of the image. The heated cathode emits larger numbers of electrons at smaller potentials and thus allows the deflecting forces to be reduced without diminishing the tube's sensitivity. The modern tube also maintains a better vacuum than could be achieved with the apparatus Braun employed.

quency currents and thus serve as detectors in radio receivers. His psilomenan detector, introduced in 1901, was the prototypical crystal detector and the first practical electronic device to employ semiconductor materials.

Early in 1915, a few months after war began in Europe, Braun visited the U.S. on behalf of the Telefunken Company; the visit was to bring a melancholy end to a brilliant career. He stayed until it became impossible for him to return to Germany. Living with his son Konrad in New York, but deprived of his laboratory and with little means to follow his interests, he was forced to spend his last years divorced from his scientific life.

When Braun died in April, 1918, the indicator tube had been improved and was being applied to investigations that prefigured the science of electron optics. He had also seen his tube perform in a novel role: as a receiver in early television systems. Max Dieckmann and Gustave Glage had patented the first picture-transmission system that incorporated a Braun tube in 1906. The following year Boris Rosing had introduced another television system that incorporated a Braun tube in the receiver. In 1908 Alan A. Campbell Swinton had suggested the use of "two beams of Kathode rays" as a solution to the almost insuperable problems of mechanical television. Three years later he had made the first detailed proposal for an electronic television system based on the "ingenious oscillograph, invented a few years ago by Braun."

All of this took place before World War I. The rapid progress made in radiophysics and electron tubes during and after the war was manifested in the sudden emergence—and popularity—of commercial radio broadcasting at the beginning of the 1920's. In 1922 the Western Electric Company introduced a gas-focused cathode ray tube that operated on low voltages with simple auxiliary circuits. This oscilloscope, a direct descendant of Braun's curve-tracing device, was portable and convenient, the ideal instrument for the booming radio industry.

Braun did not patent his indicator tube, nor did he make a concerted effort to promote it. In many respects it was a premature invention. Braun's model was operating more than seven years before the first tube of importance to radio was patented, yet the indicator tube required decades of research and technological evolution before it became the indispensable device it is today.

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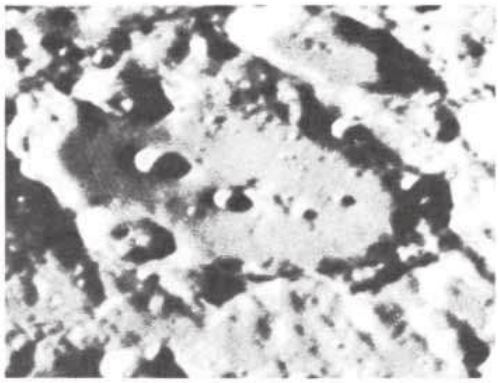

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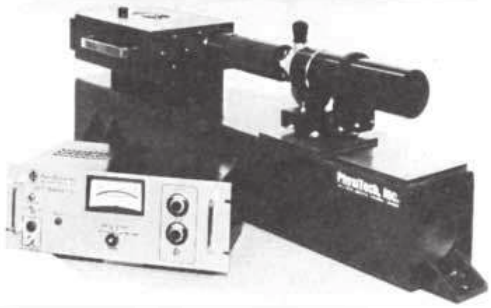

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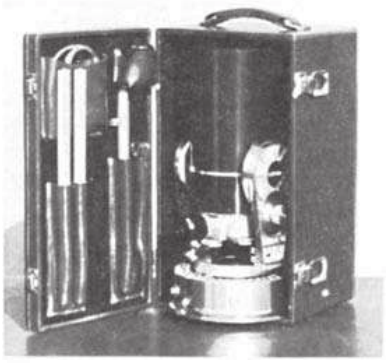

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